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(54) **Continuously transposed conductor.**

(57) A continuously and uniformly transposed electrical cable for use in inducting apparatus such as reactors or transformers and method of making the same which consists of winding simultaneously a plurality of wire strands (square, round or otherwise of cross-sectional shape) around a mandrel that is in a fixed position on the winding machine and continuously withdrawing the wound cable from the mandrel as the strands are wound therearound. The wound cable is devoid of a core strand and thus all strands in the cable are equally transposed throughout the length of the cable. The wound cable may be compacted (by roll forming) to improve the space factor by shaping the cable to a flat strip, or square or rectangular cross-sectional shape as may be required for particular applications.

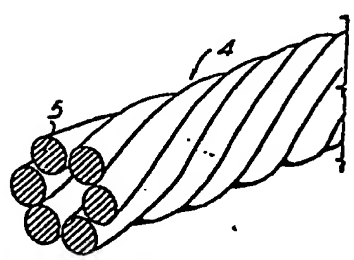

FIG.3.

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CONTINUOUSLY TRANSPOSED CONDUCTOR

This invention relates to inductive windings for electrical transformers, reactors and the like, and more particularly to low loss, flat or rectangular shaped cabled conductor for use in such equipment and a method of making the same.

In any high current or high frequency induction apparatus electrical losses occur in the windings due to skin effects and proximity effects, and it is known that such losses may be reduced by dividing the conductors of which the windings are made into small sub-conductors which may or may not be insulated from each other and which may be transposed relative to each other. For maximum efficiency the transposition of the subconductors should be such that all subconductors are linked by the same quantity of magnetic flux so as to ensure that each subconductor will have the same effective inductance and therefore each will carry its proper share of the total current.

One method for transposing subconductors for large induction equipment is described in Canadian Patent 768,775, issued to Westinghouse Electric Corp. on October 3, 1967, and employs an odd number of rectangular subconductors having a width to thickness ratio of about 3:1, arranged in two columns. Each subconductor in turn is discretely transposed at intervals along the length of the conductor. Since, however, the transpositions are made at discrete points only, a complete transposition of all subconductors in a conductor containing a large number of subconductors, takes a long length of cable to achieve. In induction apparatus where the magnetic field changes rapidly, for example in the end region or a small diameter air core reactor, it is difficult if not impossible

to achieve sufficient transpositions to ensure that the currents are shared equally by the subconductors. Eddy current losses per unit length of subconductor vary as the cube of the subconductor dimension normal to the incident magnetic field, so that rectangular subconductors are not the optimum shape for the construction of induction apparatus in which the direction of the magnetic field is different in different regions of the apparatus. For example, in large air core inductors, the field near the center plane of the reactor is axial whereas the field near the end plane of the reactor is radial. If the thin side of the subconductor is arranged to be perpendicular to the axis of the reactor, this will ensure that the eddy losses are small near the mid-plane of the reactor but it will also ensure eddy losses will be very large in the conductors near the end plane of the reactor. The optimum shape of the conductor for such apparatus would be to have subconductors that are square or round.

A cable comprising rectangular subconductors is easy to bend in a direction normal to the long side of the subconductors, but is very difficult to bend in the direction normal to the thin side of the subconductors without buckling the cable. The use of square or round subconductors facilitates bending of the main conductor in either of its principal directions.

The problems surrounding the use of rectangular subconductors are at least partially solved in a construction known in the art as a "Litz" cable (such as that sold by New England Electric Wire Corp. Lisbon N.H., which in its basic form, is essentially a standard 1 x 7 cable construction which may be roll pressed to a rectangular final cross sectional

shape. The disadvantage of this construction is that the central subconductor, or even rope, which acts as a core and around which the remaining six subconductors are continuously transposed, does not change its position, i.e. is not transposed, and consequently it does not carry its proper share of the current, and the cable therefore has a poor packing factor.

It is, therefore, an object of the present invention to provide an improved, conductor cable in which all the subconductors in the construction are continuously and equally transposed and which has an improved packing factor.

Another object of the present invention is to provide a method for producing the improved continuously transposed cable of the present invention. According to a principal aspect of this invention there is provided a method for making a continuously and uniformly transposed electrical cable, comprising:

simultaneously winding a plurality of electrical conductors around an elongate mandrel so that the conductors are in parallel side-by-side relation at a selected acute angle to the axis of the mandrel; and simultaneously with winding the conductors on the mandrel, continuously withdrawing the wound cable from the mandrel.

Also, there is provided in accordance with the present invention, a cable manufactured in accordance with the foregoing method wherein the conductors are uniformly and continuously transposed throughout the length of the cable.

The invention is illustrated by way of example with reference to the accompanying drawings wherein:

Figure 1 is an isometric view of one form of discretely transposed cable according to the prior art;

Figure 2 is an isometric view of another transposed cable of the prior art;

Figure 3 is an isometric view of a continuously transposed cable according to the present invention;

Figure 4 is an isometric view of another embodiment of the cable according to the present invention;

Figure 5 is a diagrammatic sketch of an apparatus arranged to produce the cable of Figure 3; and

Figure 6 is a diagrammatic sketch of an alternativ apparatus arranged to produce the cable of Figure 3.

Figure 1 illustrates a transposed cable of the prior art comprising an odd-numbered plurality of rectangular subconductors or strands 1, each having a width to thickness ratio of about 3:1, arranged in two columns or layers with a strand at the end of one of the layers projecting past the adjacent layer and transposed about the main axis of the cable at a specific transposition point, by means of a first discrete bend which moves the strand to the adjacent layer and a second discrete bend which moves each of the strands in the newly vacated layer, one strand position in the same layer to fill the layer. It will, of course, be appreciated that this method of transposition is not entirely uniform or continuous and, furthermore, the odd strand on the top of the layers creates a non-uniform appearanc and is relatively bulky.

Some of the problems of the cable of Figure 1 are eliminated with the cable of Figure 2 which represents the simplest and least complicated form of a "Litz" cable, in which a plurality of subconductors or strands are continuously transposed about a core conductor or strand 3. Core 3 may be an electrical conductor or may simply be an inert core such as a rope core. The strands 2 may be single conductors or may themselves consist of a number of sub-subconductors which are bunch laid or otherwise transposed, and the result is a uniformly shaped cable having a relatively poor space factor due to the presence of the non-transposed and largely electrically useless core 3. Litz cable may be roll formed to a rectangular shape or flattened and may have multilayers of unilaid conductors.

Figure 3 illustrates a cable 4 of the present invention in its simplest form and which consists of a plurality of circular insulated or uninsulated subconductors 5 cabled together without a core conductor or the like, so that each and every subconductor 5 is uniformly and continuously transposed along the length of the cable. It will, of course, be appreciated that each subconductor 5 may be a single strand or a number of bunch laid or cabled sub-subconductors which may in turn be cabled. The cable 4 may be roll formed to achieve compaction and to form the conductor into a rectangular or sheet form.

The cable 4 of Figure 3 is manufactured using a method and apparatus as illustrated schematically in Figure 5. Referring now to Figure 5 there is illustrated a plurality of cable spools 10, each carrying a supply of insulated or uninsulated conductor wire strands, rotatably mounted adjacent the periphery of a circular base member 11 which in turn is mounted on an axle 12 driven for axial rotation by means of

drive means 19. Wires from spools 10 are drawn through respective guide holes 13 in a feed strand guide 14 mounted on axle 12 for rotation therewith. The wires, as they are drawn from the spools are wound around a mandrel 15 which extends axially from axle 12 and is stationary relative thereto. The wires are drawn from the spools by means of any suitable cable gripping and drawing device shown schematically at 16. The cabled conductors are continuously drawn off mandrel 15 as they are wound therearound and downstream from the mandrel the cable may be press rolled at 17 to compress and shape the cable into a rectangular, square or sheet, i.e. thin strip cross-sectional shape as required. The cable may also be wrapped with insulation by a conventional cable wrapping device 18. A barrier strip 20, from spool 21, may be introduced between the mandrel 15 and the conductors. The conductors and barrier strip are pulled off the mandrel simultaneously so that, after roll forming, the barrier strip lies between the two sides of the conductor and prevents the subconductors from touching each other. As indicated above, the subconductors may be insulated or uninsulated depending on the importance of eddy currents in the apparatus in which the cable is to be used. Where the magnetic field strength is large and/or the frequency is high, the strands may require insulation so as to keep eddy currents small. It will be observed that if a barrier strip is introduced, as described above, during manufacture, it is only necessary to insulate every second subconductor in order to achieve full isolation between the conductors.

A slightly more complex embodiment of the invention may be achieved by using subconductors that themselves are formed from a number of sub-subconductors which are insulated

and then bunched, cabled or otherwise transposed to form a subconductor all of the sub-subconductors of which will share current uniformly.

Another more complex embodiment of the invention is illustrated in Figure 4. In this embodiment, a second layer of subconductors 45 (which may be either simple conductors or may consist of sub-subconductors) is wound in the same direction over the top of the first layer 46 after this layer has been roll formed into a compact rectangular shape so as to form a unidirectionally laid, or unilaid, cable. The second layer is also roll formed in order to compact the cable and to make its cross-section rectangular.

When a very large number of subconductors is to be used to form a sheet which is very wide and thin, the use of the rotating bobbin-stationary mandrel concept described with reference to Figure 5 becomes difficult and the continuously transposed cable may be manufactured as shown in Figure 6. In this alternative process the subconductors are drawn from an array of reels 61 rotatably mounted on a fixed frame through a strand guide 62 onto a rotating mandrel 63 by a take up reel 67. A barrier strip 64 formed into a cylinder at 65 may be introduced between the mandrel 63 and the conductor as described above. The conductor and barrier strip are slid over the rotating mandrel continuously and then roll formed at 66 to achieve compaction and to form the conductor into a rectangular or sheet form. In this embodiment the roll forming mechanism 66 must be rotated at the same speed as the mandrel 63 as must the taping machine (if provided) and the take-up reel 67. An alternative method of achieving compaction is to use subconductors which are already square in cross-section or

to use round subconductors but to roll form them (68) into a rectangular sheet prior to winding them on the rotating mandrel (63).

Cables manufactured according to the present invention offer several advantages over the transposed cables of the prior art. For example:

(a) All subconductors of the new cable are identically, continuously, and uniformly transposed. Conventional transposed cables transpose strands discretely rather than continuously.

(b) Since all strands are transposed in an identical manner, the cable has a very uniform appearance and has no projections or bulges which would make it difficult to wind.

(c) The length along the cable which is required to make a complete transposition of all subconductors can be made very short by increasing the pitch when winding the subconductors onto the mandrel. The length required for a complete transposition can be made much shorter than is possible in conventionally transposed cable.

(d) The continuously transposed cable of the present invention can be made either from rectangular subconductors or round subconductors. If round subconductors are used, the cost of making the cable is considerably less than the cost of making conventional transposed conductors which uses rectangular subconductors.

(e) Since the subconductors even after roll forming have a shape which is nearly square, the eddy loss in the subconductors can be kept very small regardless of the orientation of the subconductors with respect to the local field in the piece of apparatus in which the cable is used. For example,

the magnetic field of an air core reactor is mainly axial near the mid-plane and nearly radial in the end-plane of the reactor. Since the eddy loss per unit length of a subconductor is proportional to the cube of the dimension which is normal to the incident field, it is difficult to achieve low eddy losses in an air core reactor if rectangular subconductors are used. If the subconductors are arranged so that their thin side is norma. to the axis of the reactor, then the eddy loss in the subconductors near the mid-plane of the air core reactor will be small but the eddy loss in the subconductors near the end-plane of the reactor will be very large since the long dimension will be normal to the local field near the end-plane since this field is radial. Since the subconductors in the present cable are nearly square, their shape is nearly optimum in all regions of the air core reactor.

(f) Since the present cable can be manufactured from round conductors, a much smaller inventory of subconductors is required in order to achieve a very large variety of cable cross-sections.

(g) The continuously transposed cable is capable of being wound with either side normal to the coil axis which is not easily possible with the regular transposed conductor which consists of rectangular shaped subconductors. The shorter the pitch, the easier it is to wind the continually transposed cable with its large side normal to the coil axis.

(h) The subconductors may themselves be composed of bunched, cabled or otherwise transposed and insulated subconductors.

(i) The continuously transposed cable may be tapped at

any point. This is not easily done with many other types of transposed cable.

In order to illustrate the advantages of the present invention in practice, in both low and high frequency applications the following examples are provided.

Example 1

Comparison of Continuously Transposed Cable and Rectangular Discrete Transposed Cable in 42 MVA, VAR Compensation Reactor

The overall dimensions of this coil will be the same whether it is made with traditional rectangular transposed cable or with continuously transposed cable. However there is a significant difference in the conductor eddy losses.

Rectangular transposed cable consisted of subconductors of rectangular section. The width to thickness ratios of the subconductors were in the range of 2:1 or 3:1. Eddy loss is proportional to the cube of the dimension which is normal to the incident field. In the case of rectangular subconductors it is only possible to orientate them so that their smallest dimension sees the incident field in one part of the winding (normally the middle portion) but the larger dimension will see the largest portion of the field in another part of the winding (the end portion) and the eddy loss will be significantly higher. In the case of the continuously transposed cable the subconductors can be round or square and hence the eddy loss will be the same in all parts of the winding.

Now consider a typical rectangular subconductor of .05 by .10 with a cross-sectional area of .005 in.^{2}. The equivalent area of round subconductors from continuously transposed sheet would be .08 in. in diameter. The net saving

in eddy loss is calculated to be 10%, i.e. the round subconductor would have 10% lower eddy loss. However it must be emphasized the rectangular subconductors of .05 x .1 in. are about the smallest that existing transposing machines can handle. In the case of continuously transposed cable, subconductor sizes on the order of .05 in. in diameter were utilized with no difficulty. The eddy loss was, therefore, 39% of that for .08 in. diameter round and 29% of the rectangular subconductor (.05 x .10). The continuously transposed cable will have more subconductors.

	RECTANGULAR TRANSPOSED CABLE DESIGN	CONTINUOUSLY TRANSPOSED CABLE DESIGN
outer diameter	120"	120"
overall height	80"	80"
weight	18,000 lbs.	18,000 lbs.
I^2R loss	84 KW	84 KW
Conductor eddy loss	14 KW	4 KW
Support Structure (spider, etc) eddy loss	26 KW	26 KW
TOTAL LOSSES	124 KW	114 KW

Example 2

Comparison of Continuously Transposed Cable and Rectangular Discrete Transposed Cable in an Air Core Commutation Reactor rated 10-μH, 300 amperes r.m.s.

The ringing frequency is 4 kHz and the Q at the frequency must be approximately 250. In order to meet the Q-requirements and the rms current requirements, it can be shown that approximately 2800 strands of #30 AWG insulated copper in parallel are required. Assuming that the basic sub-conductor will comprise 80 #30 conductors in bunch lay, then 34 subconductoı

will be required.

Using the cable construction described herein, 34 subconductors each comprising 80 #30 bunched copper strands may be used to produce a flat cable about two inches wide and 0.2 inches thick. This cable will be perfectly transposed and have a packing factor of about 0.6. In the alternative it is possible to use 17 subconductors each comprising 80 bunched #30 copper strands to produce a 1 inch by 0.2 inch flat cable having a packing factor of 0.6. Two of these cables can be used in parallel providing that they are properly transposed themselves to carry equal currents.

If regular "Litz"-wire is to be made, there are several options. If only one cabling operation is permitted, then in order to guarantee perfect transposition, a type 4 Litz construction must be used which consists of 34 subconductors cabled around a central non-conducting core. The diameter of this cable will be approximately 1.2 inches and the packing factor approximately 0.19, only 1/3 of that for the continuously transposed sheet. A 17 subconductor cable would have a packing factor of only 0.26, less than 1/2 that of the continuously transposed cable.

The coil made from the continuously transposed sheet is approximately 20% lighter and 25% smaller in diameter and height for the same Q factor.

When making cable for high-frequency use, it is possible with the cable construction method described herein to perfectly transpose very large numbers of strands with only two operations (bunching and cabling) and to provide at the same time a very good packing factor (greater than 0.5). With

conventiona Litz, the only way to perfectly transpose a large number of subconductors in one pass is to use a non-conducting central cylinder about which to cable the subconductors. This provides a very poor packing factor, the larger the number of subconductors the poorer the packing factor.

CLAIMS

1. A method of making a continuously and uniformly transposed electrical cable, characterized in winding a plurality of electrical conductors around an elongate mandrel so as to be in parallel side-by-side relation therearound at a selected acute angle thereto so as to produce a uniformly transposed cable and simultaneously with winding the conductors onto the mandrel, withdrawing the wound cable from such mandrel.

2. A method as claimed in Claim 1 characterized in that the plurality of conductors are wound onto a stationary mandrel from feed means axially rotatably mounted relative to said mandrel.

3. A method as claimed in Claim 1 characterized in that the plurality of electrical conductors, in parallel side-by-side relation, are wound onto an axially rotating mandrel from feed means stationary relative to said mandrel.

4. A method as claimed in any of the preceding claims characterized in that the wound cable is roll formed to selected cross-sectional shape as it is withdrawn from the mandrel and at a position downstream from the mandrel.

5. A method as claimed in Claims 1, 2 or 3 characterized in that a barrier strip means is fed between the plurality of electrical conductors and the mandrel and that the conductors are wound onto such barrier strip means on the mandrel.

6. A method as claimed in any of the preceding claims characterized in that the wound cable is wrapped with insulation means following withdrawal from the mandrel.

7. A method as claimed in Claim 3 characterized in that the electrical conductors are flattened by a roll device located between the feed means and the mandrel.

8. An electrical cable manufactured in accordance with the method of any of the preceding claims and characterized in that there are a plurality of electrical conductors continuously and uniformly transposed throughout the length of the cable.

9. A cable as claimed in Claim 8 characterized in that each of said conductors comprises a single strand.

10. A cable as claimed in Claim 8, characterized in that each of said conductors comprises a plurality of subconductors.

11. A cable as claimed in Claim 10, characterized in that the subconductors are bunched, cabled or transposed.

12. A cable as claimed in Claims 8, 9 or 10, characterized in that there is a second layer consisting of a plurality of electrical conductors wound around the first group of conductors.

13. A cable as defined in any of the preceding Claims 8 to 12, characterized in that there are at least two layers each consisting of a plurality of conductors uniformly transposed throughout the length of the cable.

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14. A cable as claimed in any of the preceding Claims 8 to 13, characterized in that the cable is roll formed to a substantially rectangular cross-sectional shape.

15. A cable as claimed in any of the preceding claims, characterized in that the conductors rolled onto the mandrel are circular in cross-section.

16. A cable as claimed in any of the preceding Claims 1 to 14, characterized in that each of said conductors is square in cross-sectional shape.

17. An inductive device comprising two or more concentric cylindrical coils wound from one or more cables as defined in any of the preceding Claims 8 to 13.

FIG.1. (PRIOR ART)

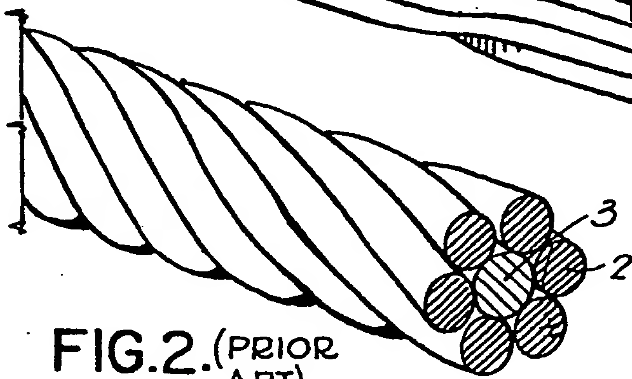

FIG.2. (PRIOR ART)

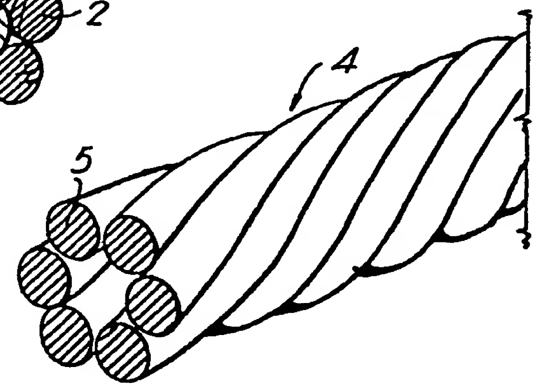

FIG.3.

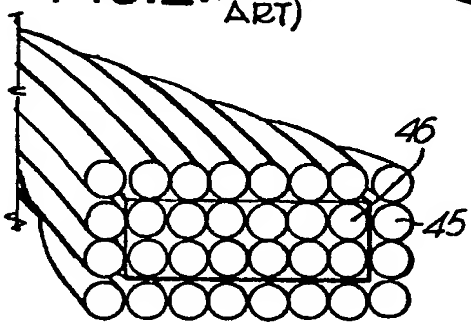

FIG.4.

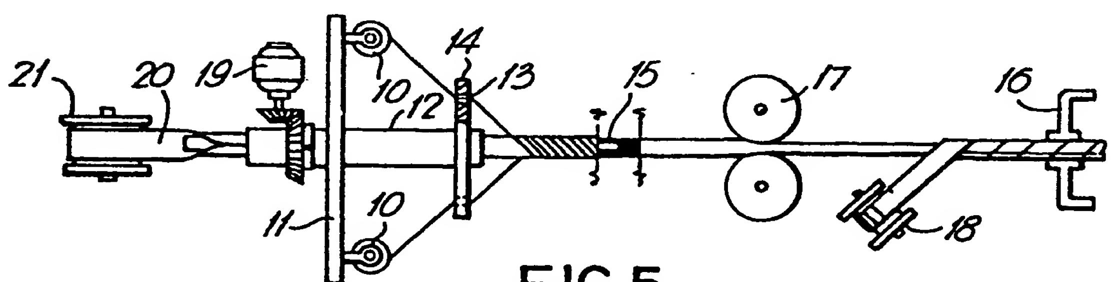

FIG.5.

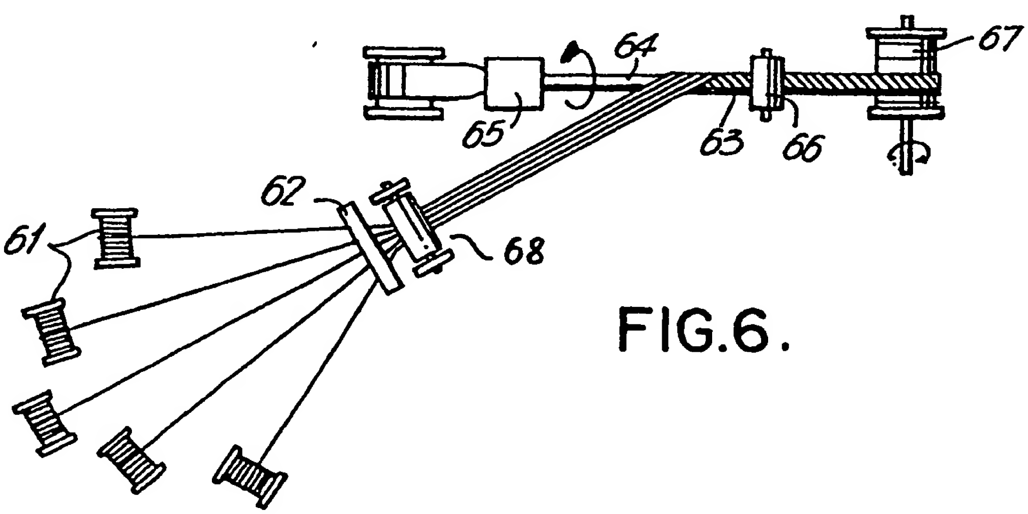

FIG.6.

European Patent Office

EUROPEAN SEARCH REPORT

0120154
Application number
EP 83 30 1704

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int. Cl. 3)
X	US-A-2 018 461 (MORGAN) * Page 2, column 2, line 6 - page 3, column 2, line 10; figures 1-5 *	1,2,6, 9,12, 15	H 01 B 13/02 H 01 B 7/30

X	US-A-1 802 302 (ZAGORSKI) * Page 3, line 81 - page 4, line 88; figures 22-24 *	1-3,9	

X	DE-A-1 665 295 (OKI DENSEN) * Page 6, paragraph 3 - page 28, paragraph 2; figures 4-9 *	1,3,4, 9,15	
	---		TECHNICAL FIELDS SEARCHED (Int. Cl. 3)
X	GB-A-1 450 678 (SCIENCE RESEARCH COUNCIL) * Page 1, line 74 - page 3, line 29; figures 1-6 *	1,2,4, 9,14, 15	H 01 B

The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
THE HAGUE	28-11-1983	DEMOLDER J.

CATEGORY OF CITED DOCUMENTS

X : particularly relevant if taken alone
Y : particularly relevant if combined with another document of the same category
A : technological background
O : non-written disclosure
P : intermediate document

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E : earlier patent document, but published on, or after the filing date
D : document cited in the application
L : document cited for other reasons

& : member of the same patent family, corresponding document